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SUMMARY

Cyclic torsion tests were made to determine the effects of varying amounts of torsional overstrain on the shape of the shearing stress-strain diagrams of the following materials: aluminum alloy 17ST, mild steel, wrought iron, copper, brass, and magnesium alloy AM57S.

The results indicate no appreciable change in the total shearing elastic range or modulus of elasticity of 17ST for varying amounts of torsional overstrain. The yield strengths for torques in the direction of the first overstrain were slightly higher than observed for torques applied subsequently in the opposite direction.

The total shearing elastic range of the mild steel and wrought iron was somewhat reduced by the overstraining. Although the moduli of elasticity indicated by the stress-strain relations for decreasing torques were essentially the same as found for the first applications of load, linear relationships between stress and strain were not found for subsequent increasing torques.

The shearing stress-strain curves for the copper, the brass, and the AM57S indicate no linear relationship between stress and strain for either increasing or decreasing torques after the first application of overstrain.

INTRODUCTION

Recent studies have shown the effects of various types of cold work or overstrain upon the stress-strain characteristics of certain metals in tension and compression. (See reference 1.) Since metals are generally selected for service uses on the basis of the properties which they exhibit in certain prescribed tests, it is obviously essential to know how the results obtained in any

case may be influenced by forming or fabrication operations prior to test.

It has been found that annealed or heat-treated metals which have not received cold work subsequent to thermal treatment, have essentially the same stress-strain curves in tension and compression. Where cold work is applied either by stretching or compressing beyond the original yield strength, dissimilar stress-strain curves in tension and compression are obtained, the higher yield strength being found in the direction of straining.

Polydirectional cold working of aluminum alloys, such as is produced by forging, cold rolling, drawing, or extruding, results in similar stress-strain curves in tension and compression with yield strengths higher than are obtained for metal free from cold working. The alternate application of overstrain in tension and compression, or cyclic overstraining, also results in similar stress-strain relations in tension and compression for aluminum alloys, provided the degree of cold work in the two directions is substantially the same. The yield strengths are generally not as high, however, as produced by polydirectional cold work. Cyclic overstraining of mild steel eliminates the characteristic yield point in both tension and compression whereas this type of cold working may materially alter the shape of the stress-strain curves for brass and magnesium. In some cases cyclic overstraining reduces the proportional limits in both tension and compression to practically zero.

The properties of metals most commonly used by engineers to determine their suitability for a given use are, of course, those determined from the tension and compression tests. The torsion test is essential, however, in the determination of shear properties. In view of the effects which cold working is known to have upon stress-strain characteristics in tension and compression, it seemed desirable that some attempt be made to determine the effects of cold working or overstraining upon stress-strain relations in shear.

The object of this investigation was to determine cyclic stress-strain curves in shear for several commercial wrought metals and to determine from the shapes of these curves the effects of varying amounts of torsional overstrain.

MATERIAL

Six different metals were tested: namely, aluminum alloy 17ST, mild steel wrought iron, copper, brass, and magnesium alloy AM57S. All the materials except the steel were obtained in the form of 3/4-inch I.P.S. tubing with a nominal outside diameter of 1.050 inches and a wall thickness of 0.113 inch. The steel tube had an outside diameter of 1-1/8 inches, which was reduced to 1.050 inches in order that it could be tested with available equipment, leaving a wall thickness of approximately 0.150 inch. The diameter-to-thickness (D/t) ratio for the steel tube was about 7, whereas for the other materials this ratio varied between 9 and 10.

The specifications to which the materials conformed are as follows:

Metal	Specification
17ST	Federal Specification WW-T-786
Steel	S.A.E. No. 1015
Wrought iron	0.07C - 0.53 Mn (no specification)
Copper	A.S.T.M. Tentative Specifications (B42-39T)
Brass	A.S.T.M. Tentative Specifications (B43-39T)
AM57S	Air Corps Specification No. 11318

The tensile, compressive, and shearing properties of these materials are summarized in table I. The copper tubing, which was received in a hard-drawn temper unsuited for the type of tests to be made, was given a partial anneal of 20 minutes at 300° C.

METHOD OF TEST

The cyclic torsion tests were made in a large lathe in the machine shop, using the set-up shown by the photograph of figure 1. This arrangement has been used with

satisfactory results in previous torsion tests. (See reference 2.) As indicated in the figure, one end of the specimen was gripped in the chuck of the lathe, which was locked in a stationary position, while the other end was supported by but free to rotate on a ball-bearing center in the tail stock. Torque was applied by dead weights suspended from a horizontal lever arm 30 inches long, clamped to the end of the tubing held in the tail stock.

Strains were calculated from twist measurements obtained by means of a Martens mirror troptometer over a 3-inch gage length. For the size of tubing tested, this gage length made it possible to read strains within ±0.00002 inch per inch.

The torsion tests were made on specimens approximately 15 inches long. The clear distance between grips was 7 inches, a length so chosen as to limit the total over-all twist to approximately 10°, for which it was not necessary to make any correction for shortening of the lever arm. Twist was measured over a 3-inch gage length with the mirror holders 2 inches from the grips. This distance was considered sufficient to give a uniform stress distribution for that part of the specimen on which the twist was measured.

In the cyclic torsion tests data for a shearing stress-strain curve were obtained in the usual manner by applying increments of torque and determining the corresponding shear strains. When deformation sufficient to produce a permanent set of approximately 0.2 percent was attained, the torque was removed in decrements and corresponding strains determined until zero stress was reached. Torque was then applied in the opposite direction and the stress-strain curve was determined to the same permanent set (0.2 percent) after which the torque was again reduced to zero by decrements. This procedure completed the loading for one cycle. The procedure was continued for two additional cycles to permanent sets of about 0.4 percent and 0.6 percent. In the case of the steel tubing, two cycles for 0.2 percent set were run.

In order to obtain permanent sets approximately equal to those specified, it was necessary to plot rough torque-strain curves during the progress of the tests. It should be emphasized that the twist-measuring device was not removed from the specimen during the entire test and that in

going from one direction to another the loading process for any one cycle was continuous. The strain readings indicated no lost mostion in the set-up in the lathe.

The shear stresses were calculated for the outer fibers of the tubing by means of the formula:

$$S_s = \frac{2Tr_1}{\pi(r_1^4 - r_o^4)}$$

where S_s maximum shear stress, pounds per square inch

T torque, pound-inches

r_1 outer radius, inches

r_o inner radius, inches

In addition to the cyclic torsion tests, standard tensile, compressive, and shearing stress-strain tests were made on all the materials, as indicated by the results in table I. Tensile tests were also made on the tubes that were subjected to torsional overstraining, in order to determine the effect of this type of cold work upon the tensile properties. In the tensile and the compressive tests, strains were measured over 2-inch gage lengths using the Martens mirror extensometer. Three-inch gage lengths were used in the shear tests, as previously indicated. The slenderness ratio (L/r) of all compression specimens was about 12.

DISCUSSION OF RESULTS

The results given in table I and figures 2 to 7 make possible a comparison of the tensile, compressive, and shear properties of the materials used. Yield strenghts in all cases were selected as the stress at which the offset from the initial modulus line was 0.2 percent. As will be noted, materials representing a wide range of mechanical properties were used. Tensile yield strengths ranged from about 44 to 90 percent of the tensile strengths. The compressive yield strengths with one exception were less than the tensile yield strengths. The differences between these properties in the case of the 17ST, the AM57S, and the annealed copper were sufficient

to indicate the effect of cold work by stretching. The 20-minute anneal at 300° C, given the hard-drawn copper tubing, was only a partial anneal. Shearing yield strengths ranged from about 48 to 65 percent of the tensile yield strengths, which agrees reasonably well with the ratios usually assumed between these mechanical properties.

Figure 8 shows the shearing stress-strain curves obtained for the 17ST. The curve from the origin to the point A, back through zero stress to the point B, and then to zero, represents one complete cycle for 0.2 percent overstrain applied in both the positive and the negative directions. The curve extending from zero stress through C and D and then back to zero, represents the second cycle, etc.

It is apparent from these curves for 17ST that cyclic overstraining in torsion had no appreciable effect upon the total shearing elastic range. The yield strengths corresponding to 0.2 percent set were somewhat higher for the torques applied in the direction of first overstrain than for the torques in the opposite direction. The moduli of elasticity indicated by the stress-strain relations for decreasing torques from the points A, C, and E, or from B, D, and F, are essentially the same as indicated by the initial modulus line in the first cycle. In general, these curves for 17ST indicate cyclic overstraining in torsion to have about the same effect on the shearing stress-strain curves that cyclic overstraining in tension and compression has upon the tensile and the compressive stress-strain curves.

The stress-strain curves shown for the steel tubing in figure 9 indicate a slight decrease in total shearing elastic range as a result of overstraining. The stress-strain relations for decreasing torques from the points A, C, E, and G, or B, D, F, and H, are essentially linear and are approximately parallel to the initial modulus line. The first loading to the point A is the only one, however, to show a definite linear relationship between increasing shearing stresses and strains, from which a yield strength and modulus of elasticity in shear might be determined.

The stress-strain curves shown in figure 10 for the wrought-iron tubing show about the same characteristic of behavior under cyclic overstraining as found for the steel tubing.

The stress-strain curves shown in figure 11 for the copper tubing indicate a behavior more unorthodox than any considered thus far. Except for the first part of the first cycle, a linear relationship between shearing stress and strain was not obtained. What appeared to be a deformation corresponding to a permanent set of 0.2 percent at point A resulted in only 0.15 percent set when the stress was returned to zero. This difference between permanent set and the departure, or offset, from the initial modulus line shows that there may be an appreciable difference between the yield strength defined on the basis of a definite permanent set and the yield strength defined on the basis of the same amount of offset. It was found by trial that the deformations for permanent sets of 0.4 percent and 0.6 percent for the second and third cycles could be approximated by measuring offsets from a line parallel to the modulus line obtained on the first loading, drawn from the point of zero stress, rather than from a line tangent to the stress-strain curve at the point of zero stress.

The stress-strain curves shown in figure 12 for the brass tubing indicate a behavior somewhere between that obtained for the wrought-iron and the copper tubing, as far as the linear relationships between shearing stress and strain are concerned. There is more difference between the shapes of the curves for stressing in opposite directions, however, than found for any of the other metals. As indicated in the figure, points A, C, and E fall almost on a horizontal line, indicating a marked yield point in this direction. As a result, the permanent sets for the upper curves of the second and the third cycles exceed somewhat the limits of 0.4 and 0.6 percent intended. The stress-strain relations obtained when overstrain in one direction was removed by straining in the opposite direction were more gradual curves.

The stress-strain curves shown in figure 13 for the AM57S tubing indicate characteristics of behavior similar to those already described. The results obtained by torsional overstraining on this material were not quite so unusual as found when alternate overstrains in tension and compression were applied. (See reference 1.)

The shape of the stress-strain curves for the copper, the brass, and the AM57S after the first application of overstrain raises several pertinent questions regarding the interpretation and the possible significance of such

results. Single torsion tests have not shown shearing stress-strain relations of the kind observed in the second and the third cycles, suggesting that the material tested had not been subjected to previous torsional overstrain or that a time factor connected with the relaxation of strain was eliminated in the continuous tests.

Table II and figures 2 to 7 show a comparison between the tensile properties of the original material and the tensile properties of the tubes which had been subjected to cyclic torsion. It is apparent from these data that the tensile properties were not materially influenced by torsional overstraining. The greatest differences were found in the case of the yield strengths of the wrought iron and the annealed copper.

CONCLUSIONS

The following conclusions are based upon the results of these cyclic torsion tests on several wrought metals:

1. The shearing stress-strain characteristics of all the metals were not affected in the same manner by torsional overstrain.

2. Torsional overstrain had about the same effect upon shearing stress-strain relations that overstrain in tension and compression had upon the tensile and the compressive stress-strain relations of the same metals.

3. The total elastic range of 17ST, as indicated by the extent of the linear relationship between shearing stress and strain, was little affected by straining beyond the elastic limit, first in one direction and then in the opposite direction. The total shearing elastic range of steel and wrought iron was reduced somewhat by this straining procedure; while, for the annealed copper, brass, and AM57S, a linear relationship between shearing stress and strain was not obtained after the first application of overstrain.

4. Torsional overstrain, as produced in these tests, had almost no effect upon the tensile properties of the materials investigated.

5. The lack of a linear relationship between shear-

ing stress and strain, as found in a number of the repeated load tests, raises several questions of fundamental importance regarding the significance and the proper interpretation of such experimental data. The tests described in this report can only be considered as preliminary in pointing out some interesting and important phenomena regarding stress-strain relations.

Aluminum Research Laboratories,
Aluminum Company of America,
New Kensington, Penna., August 13, 1940.

REFERENCES

1. Templin, R. L., and Sturm, R. G.: Some Stress-Strain Studies of Metals. Jour. of the Aero. Sciences, vol. 7, no. 5, March 1940, pp. 189-98.

2. Moore, R. L., and Paul, D. A.: Torsional Stability of Aluminum Alloy Seamless Tubing. T.N. No. 696, NACA, 1939.

TABLE I

SUMMARY OF TENSILE, COMPRESSIVE, AND SHEARING PROPERTIES OF TUBING AS RECEIVED

Material	Tensile strength (lb/sq in.)	Tensile yield strength, offset=0.2% (lb/sq in.)	Ratio: $\frac{T.Y.S.}{T.S.}$	Elongation in 2 in. (percent)	Compressive yield strength,[1] offset=0.2% (lb/sq in.)	$\frac{C.Y.S.}{T.Y.S.}$	Shearing yield strength, offset=0.2% (lb/sq in.)	Ratio: $\frac{S.Y.S.}{T.Y.S.}$
17ST	65,950	45,000	68.2	25	37,400	83.2	22,000	48.9
Steel	82,380	74,500	90.5	19	72,500	97.3	48,500	65.1
Wrought iron	46,720	24,800	53.1	61	24,600	99.2	15,250	61.5
Copper (annealed)	40,540	21,200	52.3	43	18,500	87.3	10,100	47.6
Brass	61,670	27,300	44.3	53	28,800	105.4	15,400	56.4
AM57S	41,240	20,200	49.0	15	16,300	80.7	10,500	52.0

[1]Determined on specimens with slenderness ratio (L/r) of 12.

TABLE II

COMPARISON OF TENSILE PROPERTIES OF TUBING BEFORE AND AFTER CYCLIC TORSION TESTS

Material	Tensile strength (lb/sq in.)		Yield strength (lb/sq in.)		Elongation in 2 in. (percent)	
	Before	After	Before	After	Before	After
17ST	65,950	65,830	45,000	44,000	25	25
Steel	82,380	82,030	74,500	76,000	19	18
Wrought iron	46,720	47,020	24,800	29,400	61	68
Copper (annealed)	40,540	40,840	21,200	24,500	43	43
Brass	61,670	62,120	27,300	28,700	53	50
AM57S	41,240	41,070	20,200	19,500	15	15

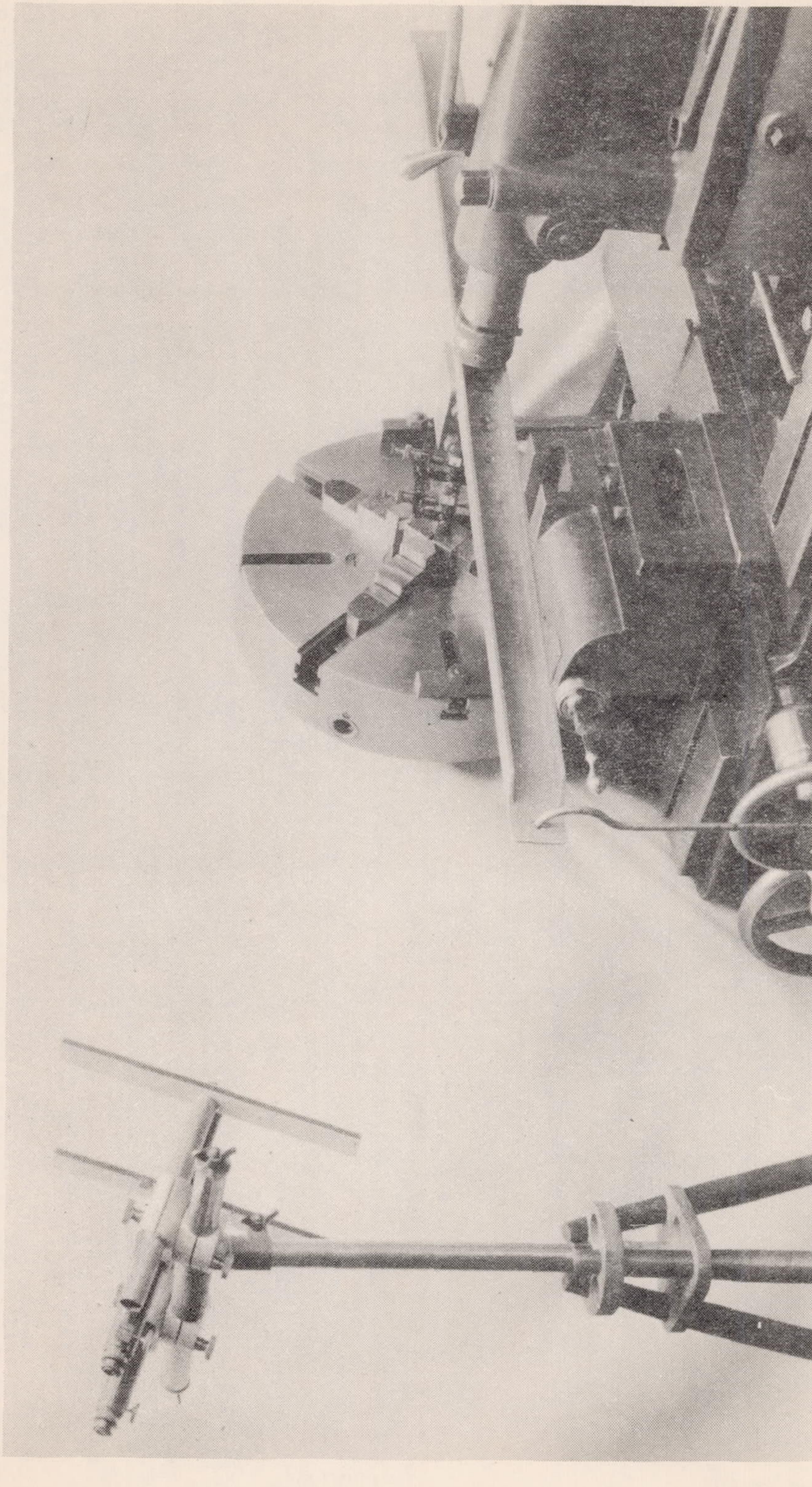

Figure 1.- Apparatus for making cyclic torsion tests.

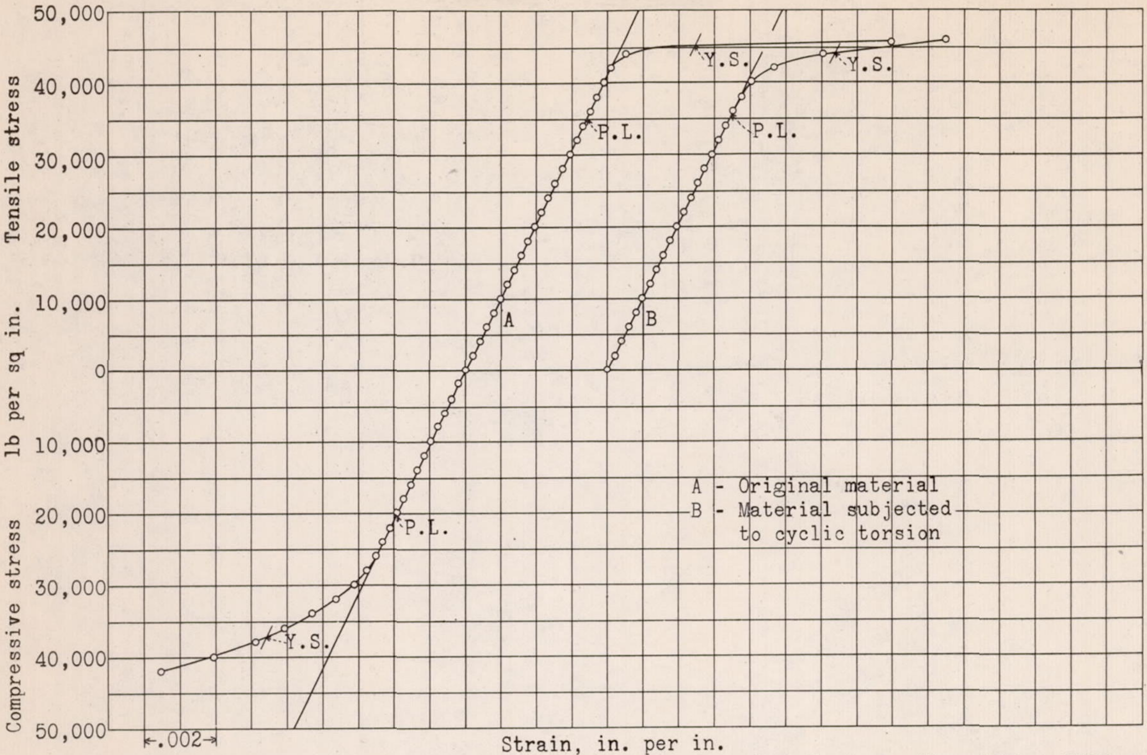

Figure 2.- Tensile and compressive stress-strain curves for aluminum alloy tubing,17ST.

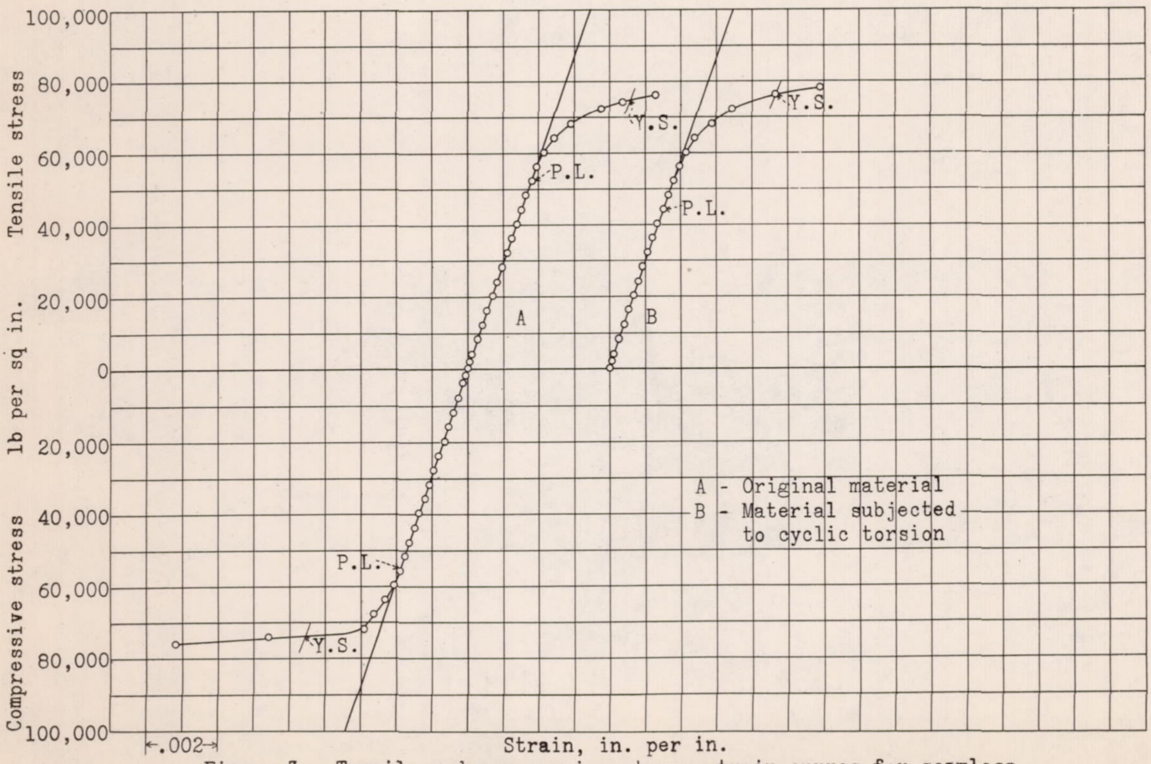

Figure 3.- Tensile and compressive stress-strain curves for seamless steel tubing, S.A.E. 1015.

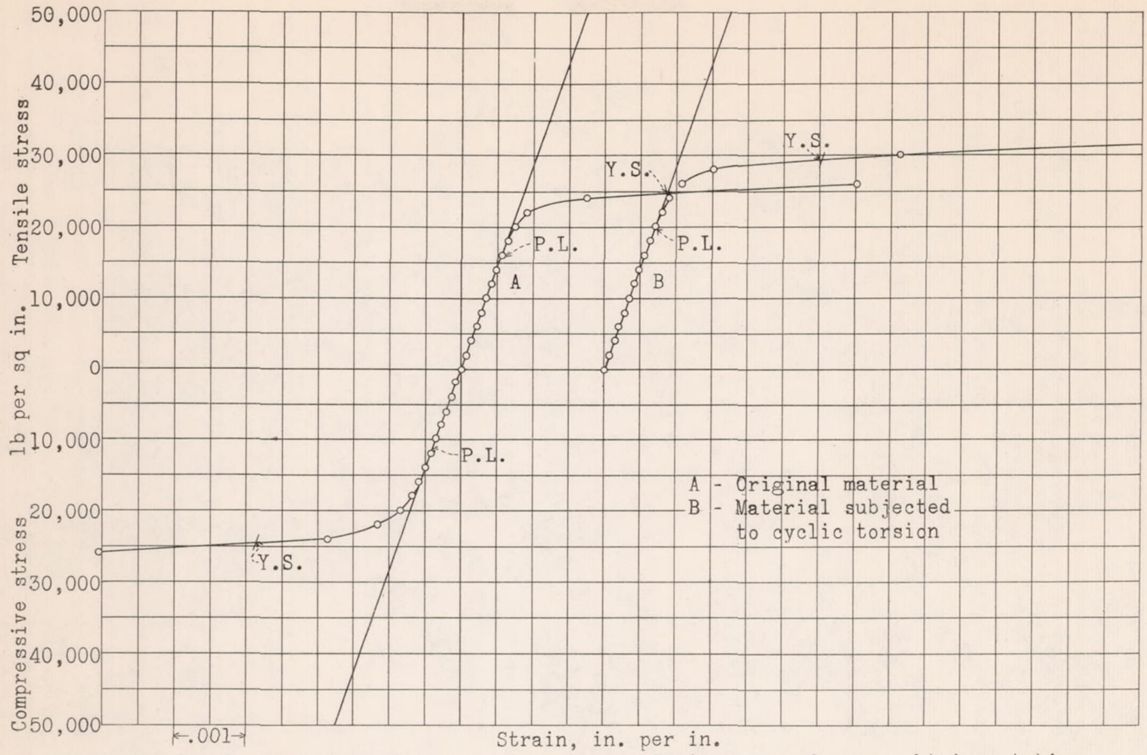

Figure 4.- Tensile and compressive stress-strain curves for wrought iron tubing.

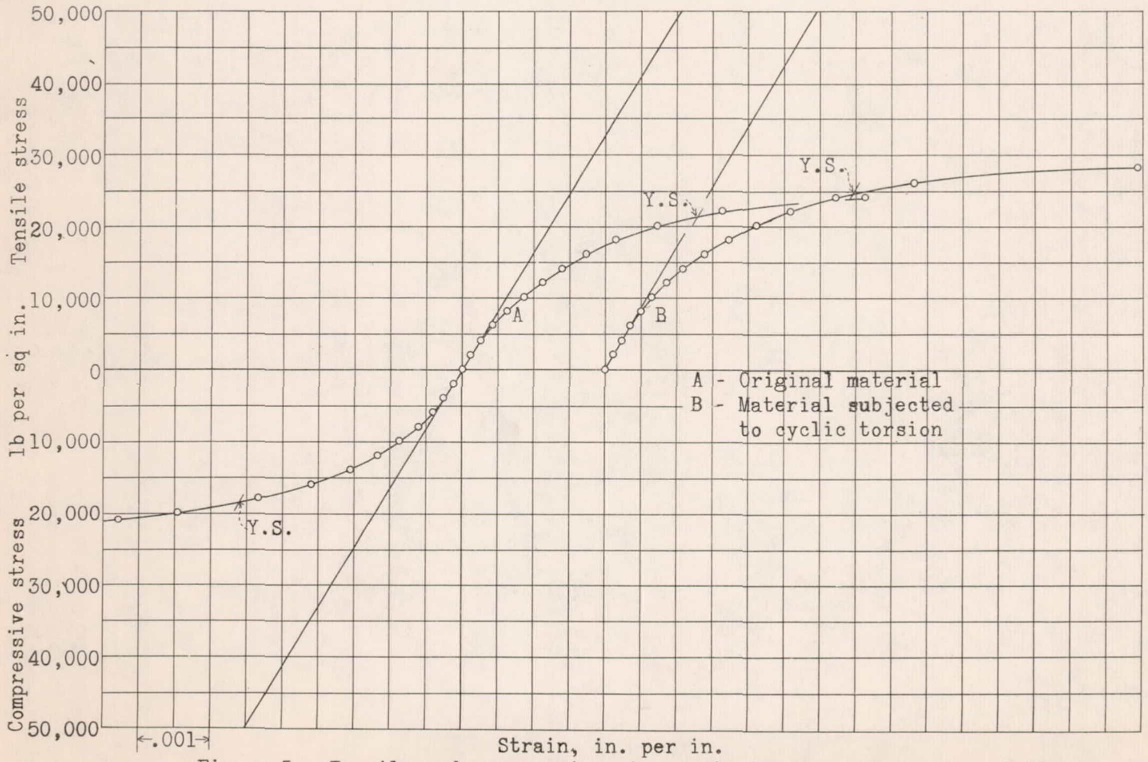

Figure 5.- Tensile and compressive stress-strain curves for copper tubing. Hard drawn copper annealed 20 minutes at 300°C.

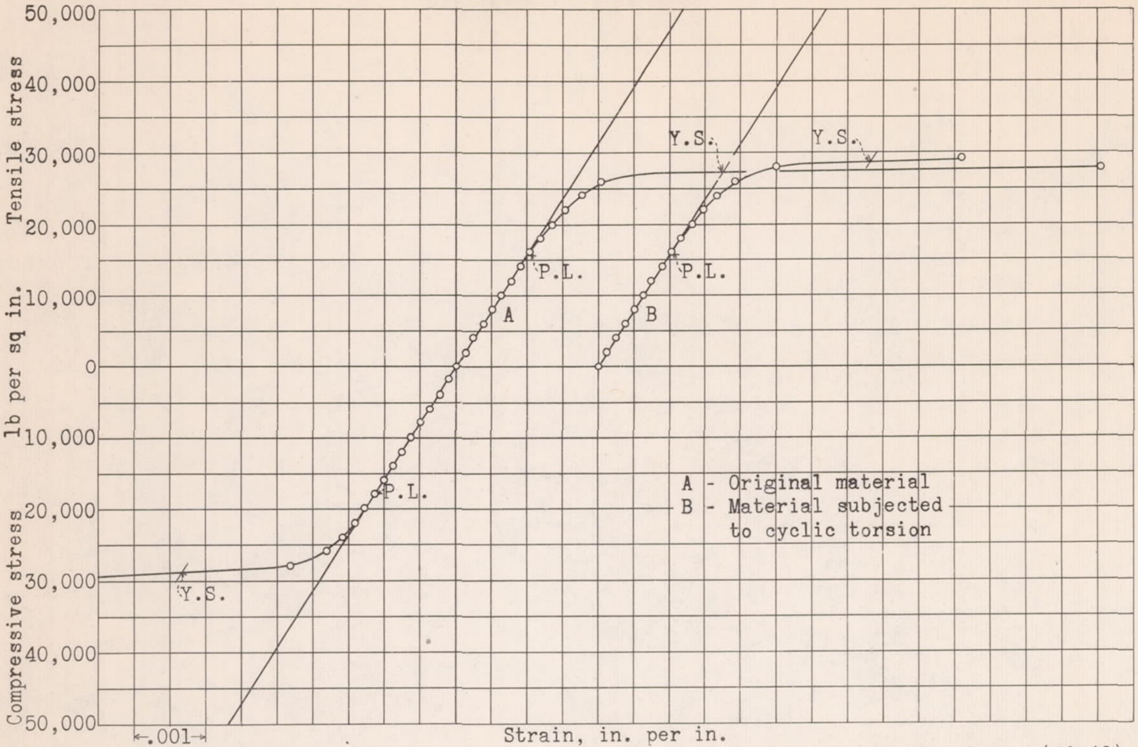

Figure 6.- Tensile and compressive stress-strain curves for brass tubing,brass (60:40).

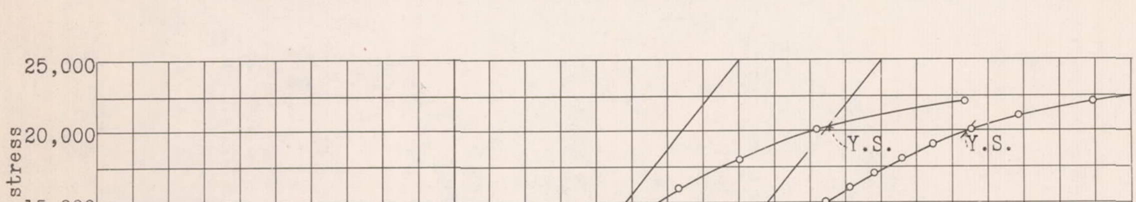

Figure 7.- Tensile and compressive stress-strain curves for magnesium alloy tubing,AM57S.

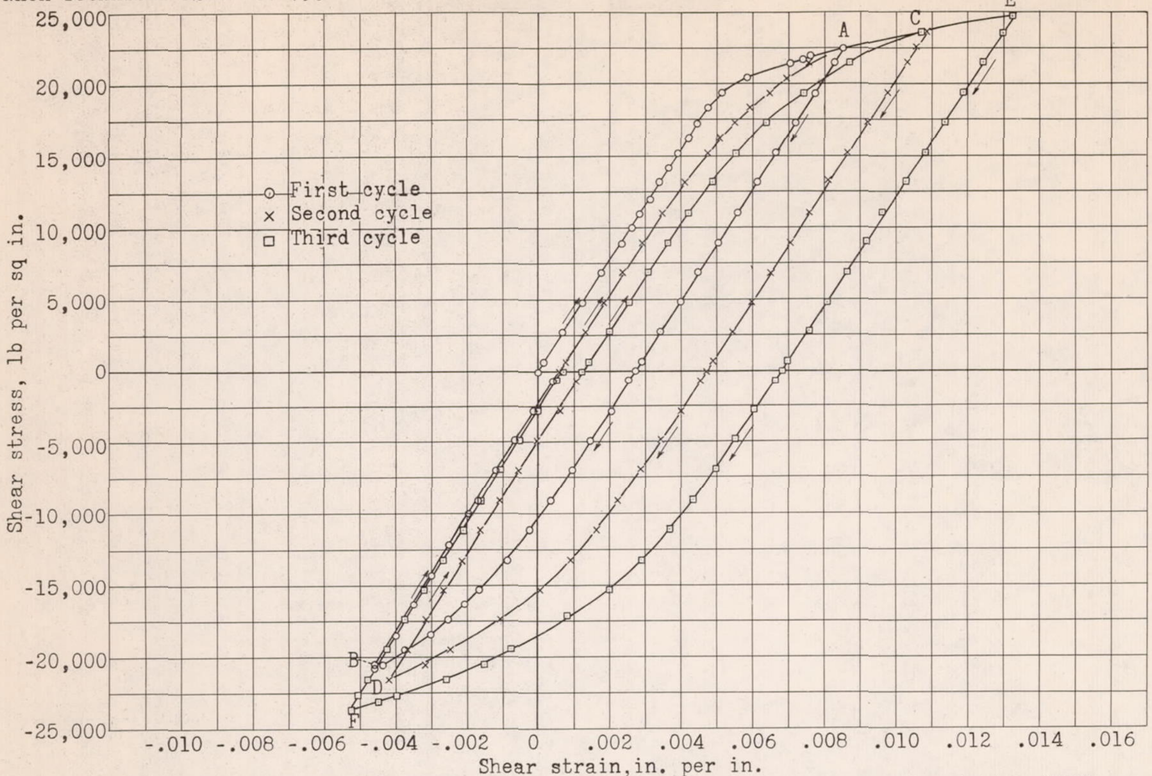

Figure 8.- Cyclic torsional stress-strain curves for aluminum alloy tubing,17ST.

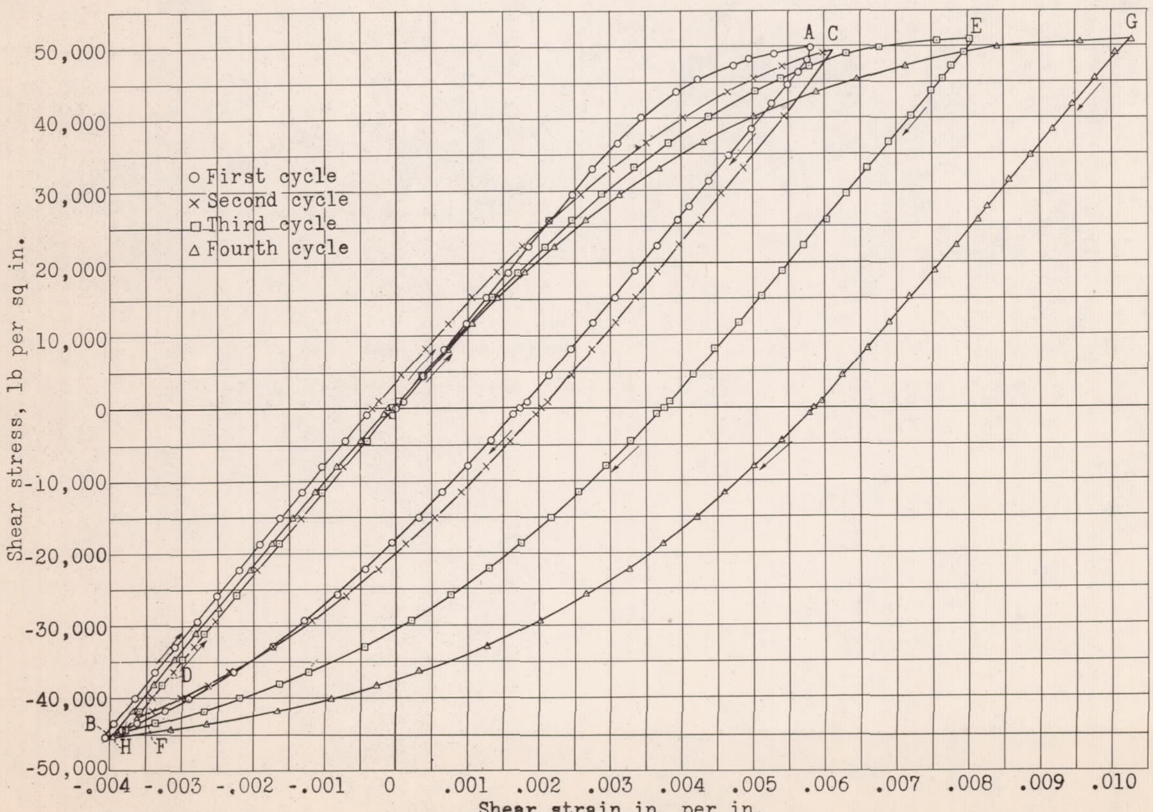

Figure 9.- Cyclic torsional stress-strain curves for seamless steel tubing,S.A.E.1015.

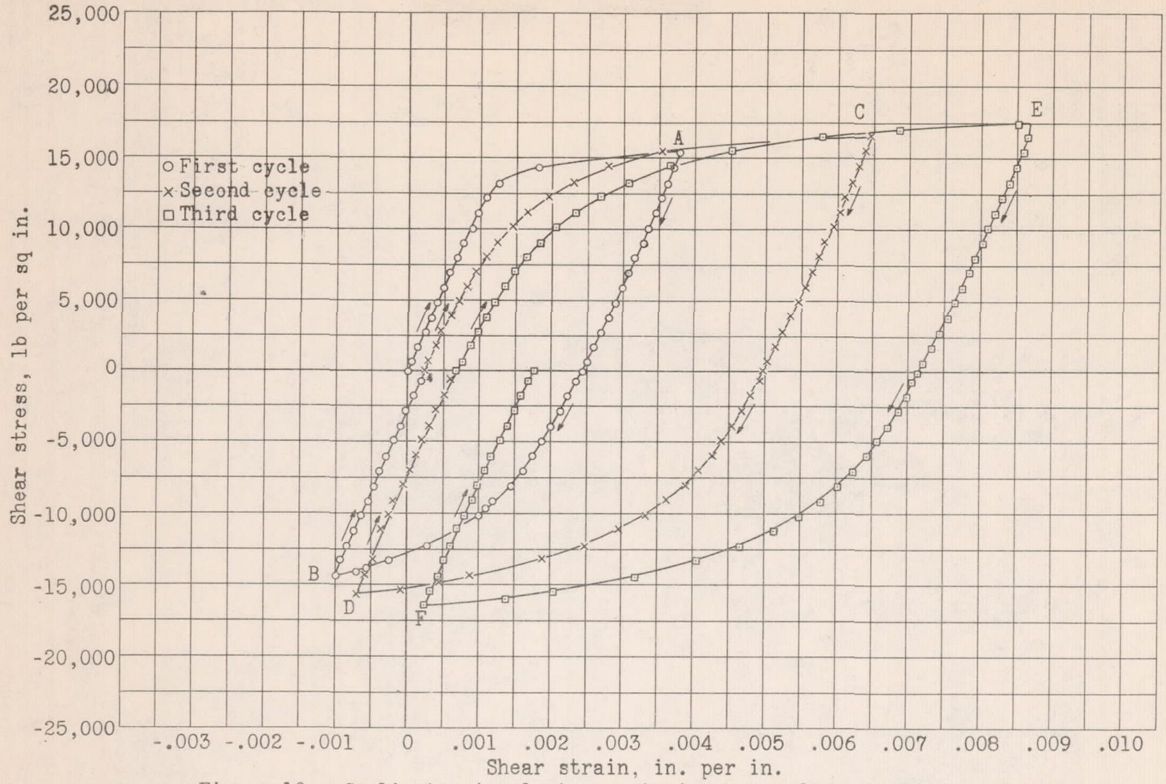

Figure 10.- Cyclic torsional stress-strain curves for wrought iron tubing.

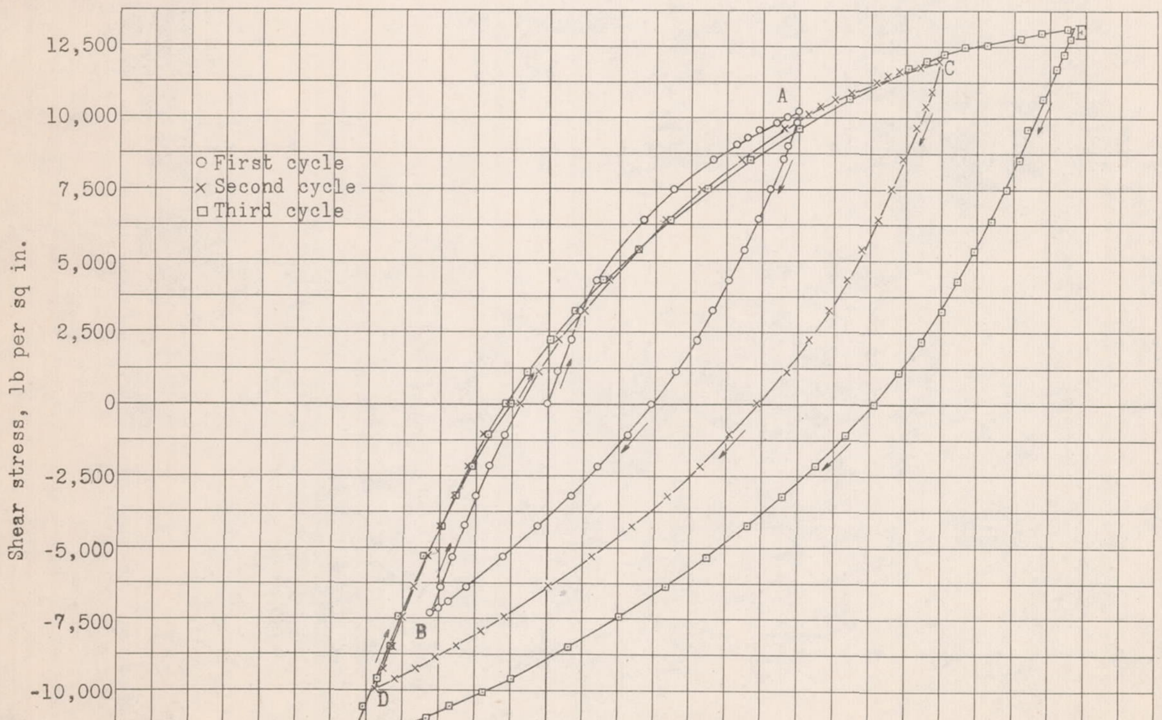

Figure 11.- Cyclic torsional stress-strain curves for copper tubing. Hard drawn copper annealed 20 minutes at 300°C.

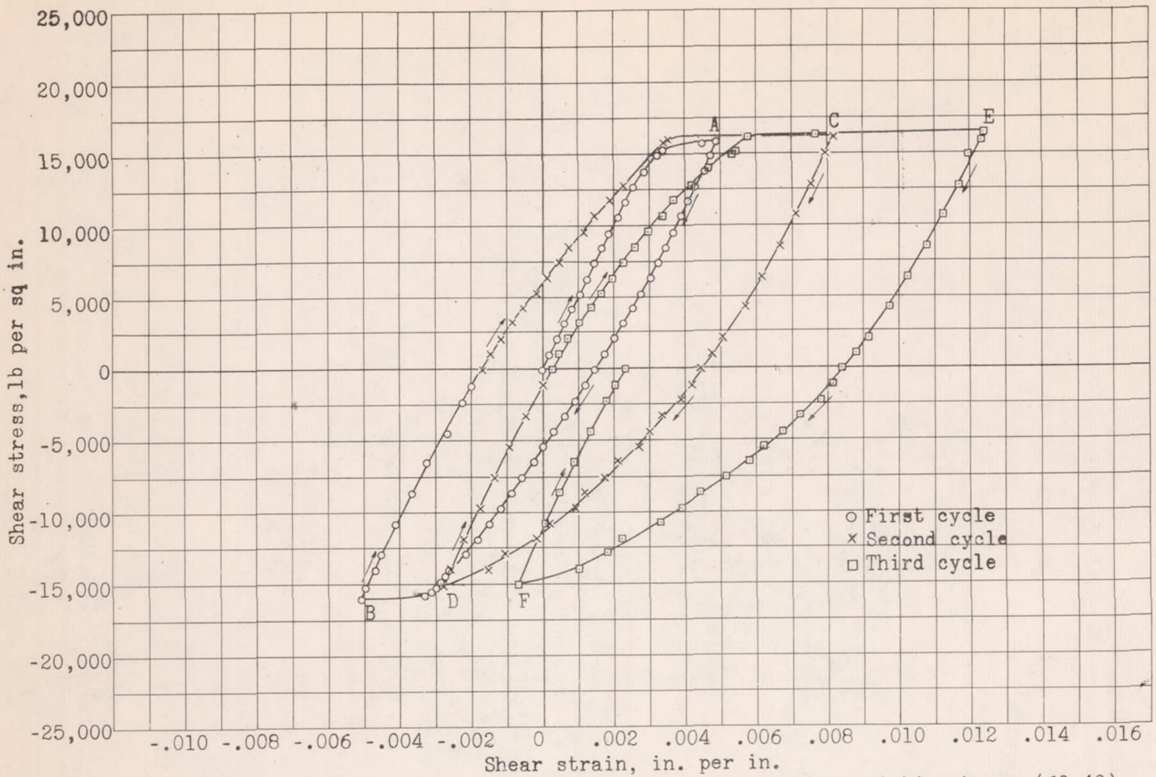

Figure 12.- Cyclic torsional stress-strain curves for brass tubing, brass (60:40).

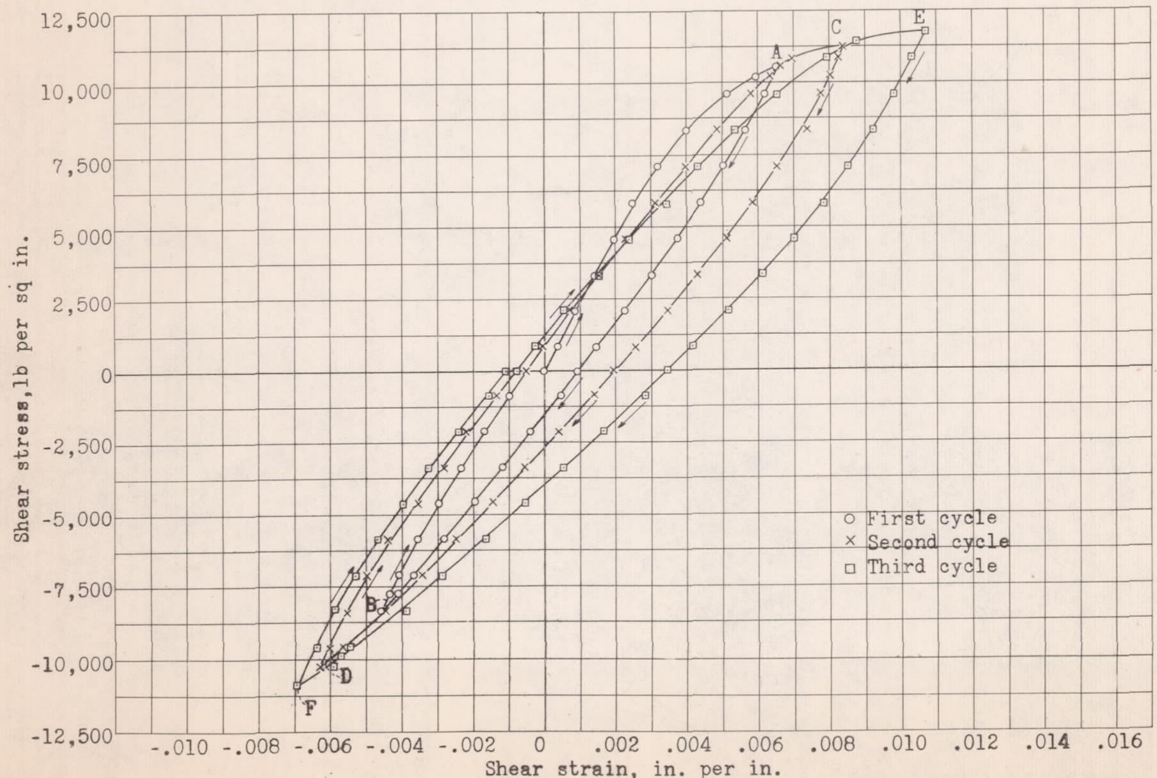

Figure 13.- Cyclic torsional stress-strain curves for magnesium alloy tubing, AM57S.